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The aims of this program were to build prototype two qubit gates for photons and to develop a blue-print for multi-qubit devices using linear optics and single photonics.

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Experimental Implementation of Efficient Linear Optics Quantum Computation

Final Report

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1. Statement of Problem.

One of the earliest proposals [1] for implementing quantum computation was based on encoding each qubit in two optical modes, each containing exactly one photon. However it is extremely difficult to unitarily couple two optical modes containing few photons. In 2001 Knill, Laflamme and Milburn (KLM) found a way to circumvent this restriction and implement efficient quantum computation using only passive linear optics, photodetectors, and single photon sources [2]. This *efficient* linear optical quantum computing (LOQC) is distinct from other linear optical schemes [3] that are not efficiently scalable.

The technological requirements for even the simplest gates in the KLM proposal initially seemed out of reach. However, Ralph, White, Munro and Milburn [4] soon showed that in principle demonstrations of key gates and techniques could be achieved with current technology.

The objective of the research undertaken in this project was to produce, in three years, a prototype two qubit gate for photons using the KLM linear optics quantum computation approach, and to develop a blue-print for a multiple qubit device that might be implemented over a longer time scale. A non-deterministic two qubit gate was demonstrated that operates with high fidelity. A number of key tasks were demonstrated using this gate. Several theoretical investigations of short, medium and longer term issues for the LOQC approach were successfully completed.

2. Summary of Key Results.

Demonstration of an Entangling 2 Qubit Gate:

We constructed and observed the quantum operation of an LOQC Controlled-NOT (CNOT) gate. The gate was based on our theoretical proposal ["Quantum optical CNOT gate", T.C.Ralph, PCT/AU02/01115 (2001), T. C. Ralph, N. K. Langford, T. B. Bell and A. G. White, Physical Review A **65**, 062324 (2002)]. It was constructed as shown schematically in Fig.1. Key design features are: the use of polarization displacers to produce a stable interferometric arrangement and the use of wave-plates to produce beam mixing in a precise ratio.

Measurement	**Value**
Output fidelity for input state 00	97%
Output fidelity for input state 01	98%
Output fidelity for input state 10	89%
Output fidelity for input state 11	90%
Average gate fidelity for truth table	93.5%
Average gate fidelity over 71 input states	95%

Table 1. Summary of data from optical CNOT gate.

The operation of the gate is non-deterministic but unambiguously quantum. This was determined by measuring the output density matrices for the logical-input data (i.e. the 00, 01, 10, 11 inputs), and, more significantly, for superposition inputs - in the latter case the outputs are entangled. We measured both the fidelity of the output states with the ideal expected Bell-state outputs (e.g. 92% for the singlet state $|01\rangle$-$|10\rangle$) and the tangle and linear entropy of the output states (respectively 79% (100% optimum) and 16% (0% optimum) also for the singlet). See table 1 for a summary. This work was published as J.L.O'Brien, G.J.Pryde, A.G.White, T.C.Ralph and D.Branning, Nature **426**, 264 (2003).

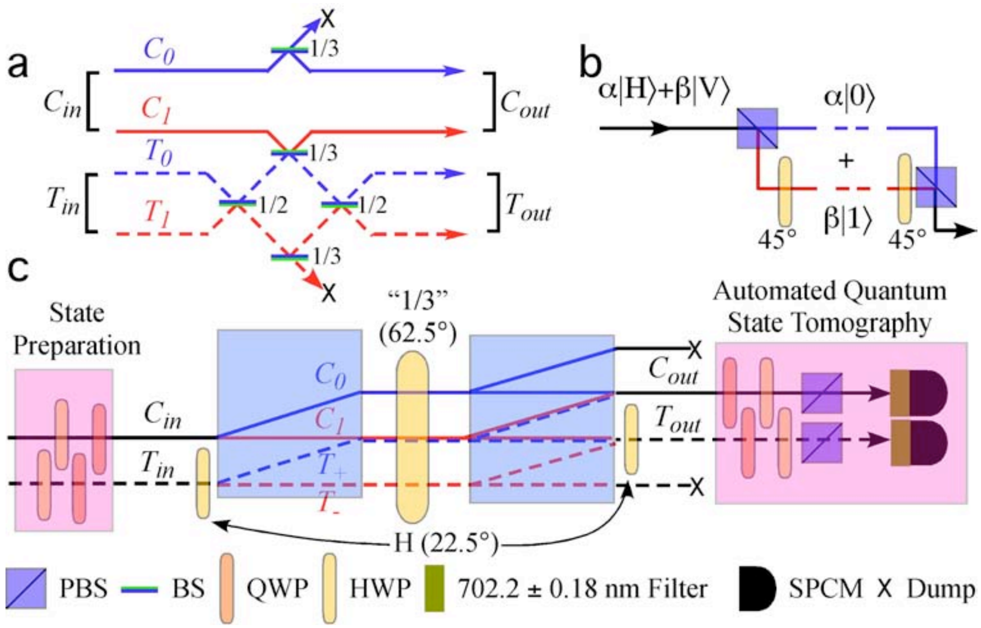

Fig. 1 A schematic of the CNOT gate. (a) A conceptual depiction of the gate, as described in previous reports. A sign change (π phase shift) occurs upon reflection off the green side of the beamsplitters (b) A polarisation encoded photonic qubit can be converted into a spatially encoded qubit, suitable for the gate shown in (a), using a polarising beamsplitter and a half wave plate set to rotate the polarisation of one of the outputs by 90^0 (optic axis at 45^0). The rotation is required so that all components of the spatial qubits have the same polarisation and can interfere both classically and non-classically. The reverse process converts the spatial encoding back to polarisation encoding. (c) A schematic of the experimental CNOT gate. Pairs of energy degenerate photons are incident from the left of the diagram. These were generated through beam-like spontaneous parametric downconversion and collected into single mode optical fibres (as described in previous reports). The output of each fiber is collimated and a HWP and QWP in each input beam allows preparation of any pure, separable two qubit state to be input into the gate. The horizontal and vertical components of the qubits are separated and recombined using PBS made from the birefringent material calcite, where the output modes are parallel and displaced. This interferometer is inherently stable, being insensitive to translation of the PBSs. The two outputs are polarisation analysed using an automated tomography system consisting of a computer controlled HWP and QWP followed by a PBS in front of each single photon counting module (SPCM). Simultaneous detection of a single photon at each of the detectors - a coincidence count - signals that the gate has worked. A coincidence window of 5 ns was used throughout.

Demonstration of Quantum Non-demolition Measurements of Optical Qubits:

The CNOT gate, as well as being a key processing device in quantum computation, is also a key measurement device. At the simplest level it allows an ideal projective or quantum non-demolition (QND) measurement to be made on a single qubit. This is achieved by preparing the target input to the CNOT in a particular computational basis state and then measuring its value after the gate. The target acts as a "meter" to measure the value of the control qubit (which is referred to as the "signal"). If the meter is found to be in the same state as prepared then the signal has been measured to be "0". If the meter is found in the opposite state then the signal has been measured to be "1". The signal photon has not been destroyed by the measurement, but instead has been projected into the state corresponding to the measurement result. We adapted our two photon CNOT gate to perform this type of measurement. The conceptual arrangement is shown in Figure 2 and the experimental results are summarized in Table 2.

We introduced generalizations of the standard QND criteria [5] in order to characterize the performance of the measurements. The measures address the issues of: measurement accuracy; signal preservation and; signal meter correlation, in terms of classical measurement fidelities. Our technique performs well against all these measures with fidelities ranging between ~80-100%.

Although closely related to our CNOT gate, there are a couple of distinct features of the QND gate which we highlight:
(i) Because the target (meter) is in a known state, the loss present in the target arm for the full CNOT can be avoided thus enhancing the success probability of the gate from 1/9 to 1/6 (when signal loss is included) or on average 1/3 if the signal loss is not included. The removal of the target (and signal) loss is achieved experimentally by inserting additional wave-plates between the beam displacers that form the gate.
(ii) Like the CNOT gate the QND measurement is non-deterministic. Unlike the general operation of the CNOT gate, the QND measurement produces a free propagating signal qubit photon when successful, so in principle the measurement works outside the realm of coincidence detection. However, in practice the lack of high efficiency photon number resolving detectors and high efficiency sources means our demonstration presently still relies on coincidence detection.

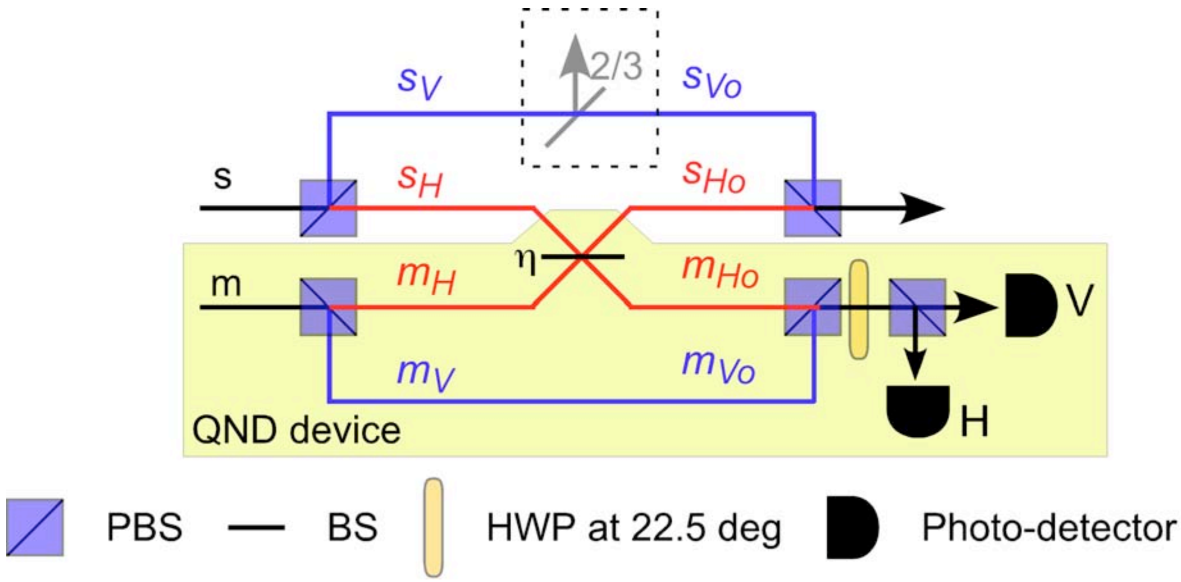

Fig.2: Conceptual layout of the QND device. The signal input is labelled **s** and the meter input is labelled **m**. The central beamsplitter has reflectivity $\eta = 1/3$. In principle, detection of a single photon at the meter output indicates success, with the measurement result given by the detector triggered (H or V). In practice, coincidence detection is needed to overcome detection and source inefficiency. The 2/3 beamsplitter can be added to equalize the probability of a successful measurement for all inputs.

Signal input	$\|H>_s$	$\|V>_s$	$\|D^+>_s$	$\|R^+>_s$
P_{HH}	0.97	0.012	0.44	0.46
P_{HV}	0.024	0.00013	0.016	0.022
P_{VH}	0.007	0.18	0.10	0.104
P_{VV}	0.0005	0.81	0.44	0.41

Table 2: Probabilities, P_{IJ}, of obtaining signal measurement result "I" if meter is found in "J" for various signal states.

Our measurement device can be simply modified so that the strength of the measurement is smoothly varied from weak to strong. This is an example of a generalized measurement and demonstrates that the QND measurement is coherent (a key requirement for quantum computation applications). We achieve this by changing the state of the meter input. If the meter is prepared in the diagonal state then the meter measurements are completely uncorrelated with the signal state and no measurement is performed. On the other hand, as we have seen, if the meter is prepared in H (say) then a strong QND measurement is performed. By varying the meter input between these two extremes a measurement of arbitrary strength can be performed. It can be shown that in principle this is an ideal measurement in the sense that only the minimum level of decoherence consistent with the knowledge obtained from the measurement result is introduced. We have tested this operating mode of our device experimentally by injecting the signal in the diagonal state, weakly to strongly measuring the path taken by the photon through the signal interferometer (see Figure 3), and then measuring the decoherence induced on the signal as quantified by its visibility. This is a strong test of the complementarity of wave-particle duality. In Figure 3 we plot the trade off between path knowledge and output visibility as measured in our experiment as a function of increasing QND measurement strength. The visibility squared and knowledge squared would ideally sum to 1 [6]. This work was published as G.J.Pryde, J.L.O'Brien, A.G.White, S.D.Bartlett and T.C.Ralph, Phys. Rev. Lett. **92**, 190402 (2004).

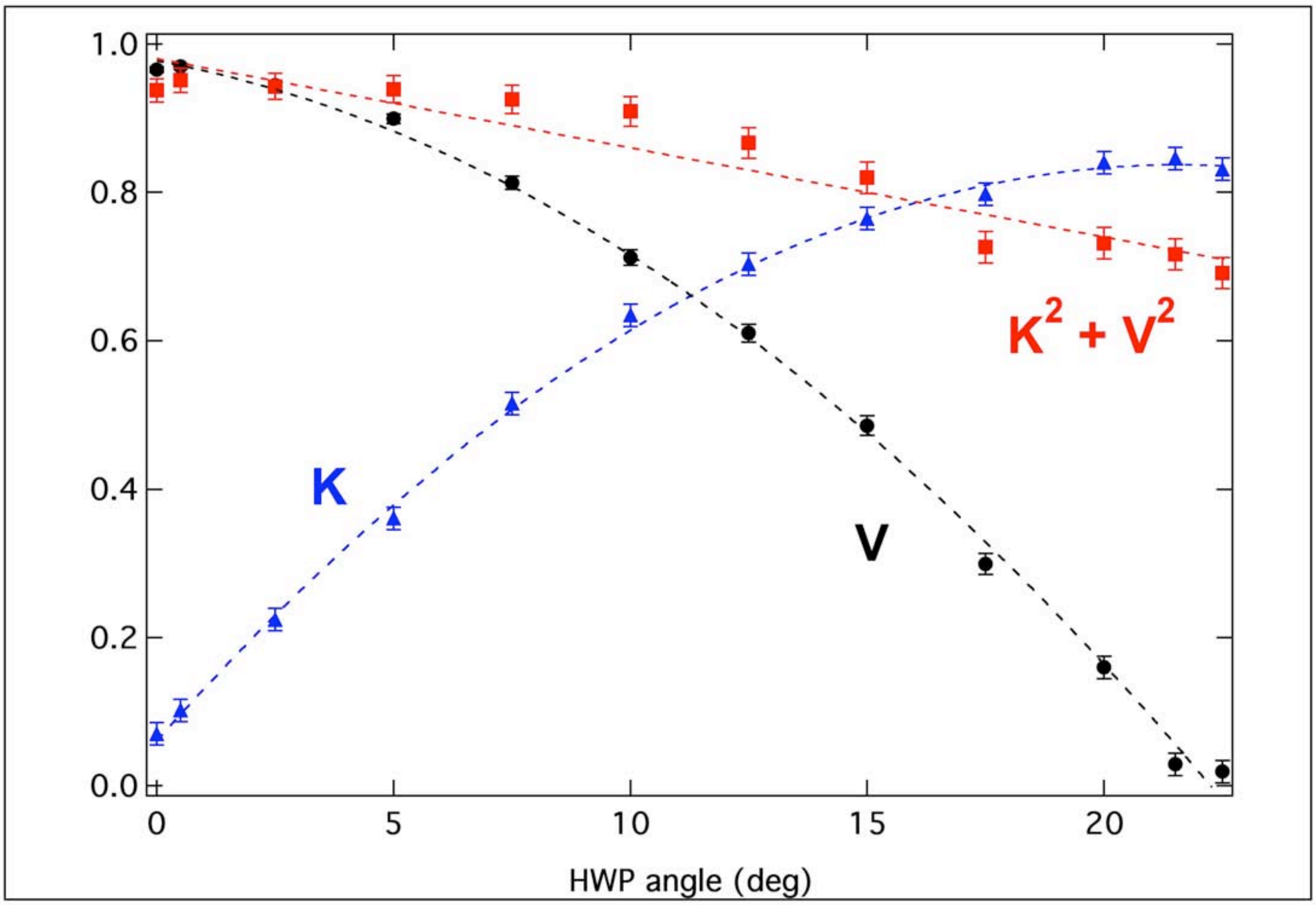

Fig 3: Plot of which-path knowledge (K), signal output visibility (V) and the sum of their squares as a function of meter input polarization. An ideal generalized QND measurement would achieve $K^2+V^2=1$ for all angles. The dotted lines are guides for the eye.

Quantum Process Tomography:

A key, and commonly overlooked, aspect of quantum gate demonstrations is the complete characterization of the gate performance. We have fully characterized our two-photon CNOT gate using quantum process tomography (QPT) and, as a result, investigated some important principles of characterizing real-world quantum circuits.

A complete and unique description of a quantum circuit - a process (or χ) matrix, can be obtained by QPT [7]. For a two qubit circuit, such as our CNOT gate, this requires measurements with 256 combinations of input and analyser settings. We address a significant, but less well known, problem in QPT experiments: that the naive matrix inversion procedure, when performed on real (i.e., inherently noisy) experimental data, typically leads to an unphysical process matrix, making its predictive power questionable. The generation of a maximum-likelihood process matrix from noisy data not only requires a least-squares fit to a parametrized Hermitian matrix, but also incorporation of sixteen extra constraints that ensure that the process is represented by a *completely positive* map - one that generates valid output density matrices regardless of whether or not the qubits are entangled to anything in their environment. Our implementation of QPT is the first full characterization of a two-qubit entangling gate, and the first demonstration of any experimental tomography that explicitly takes into account the complete positivity of the map that the process matrix represents.

The process matrix of our CNOT gate is shown in Figure 4, along with that of an ideal CNOT. The main deviation from ideal CNOT behaviour is observed in the population of the $I \otimes I$ element, which is much larger than the ideal. Because of imperfect mode matching in the circuit, the gate sometimes fails to implement the CNOT transformation. Fortunately imperfect mode matching is not a fundamental issue and should be addressable in the medium term using guided wave techniques.

From the process tomography we are able to extract the "process fidelity", a quantity from which various measures of the gate performance can be determined, such as the average gate fidelity, which is 0.90 for our gate. It is not practically possible to obtain error estimates on the process fidelity when calculated from the process matrix, due to the many-parameter numerical minimization. However, we have found a means of using a 71-element subset of the tomographic data to directly calculate the process fidelity and error. This yields a value for the average gate fidelity of 0.95 ± 0.01, where the main source of error is assumed to be from Poissonian counting statistics.

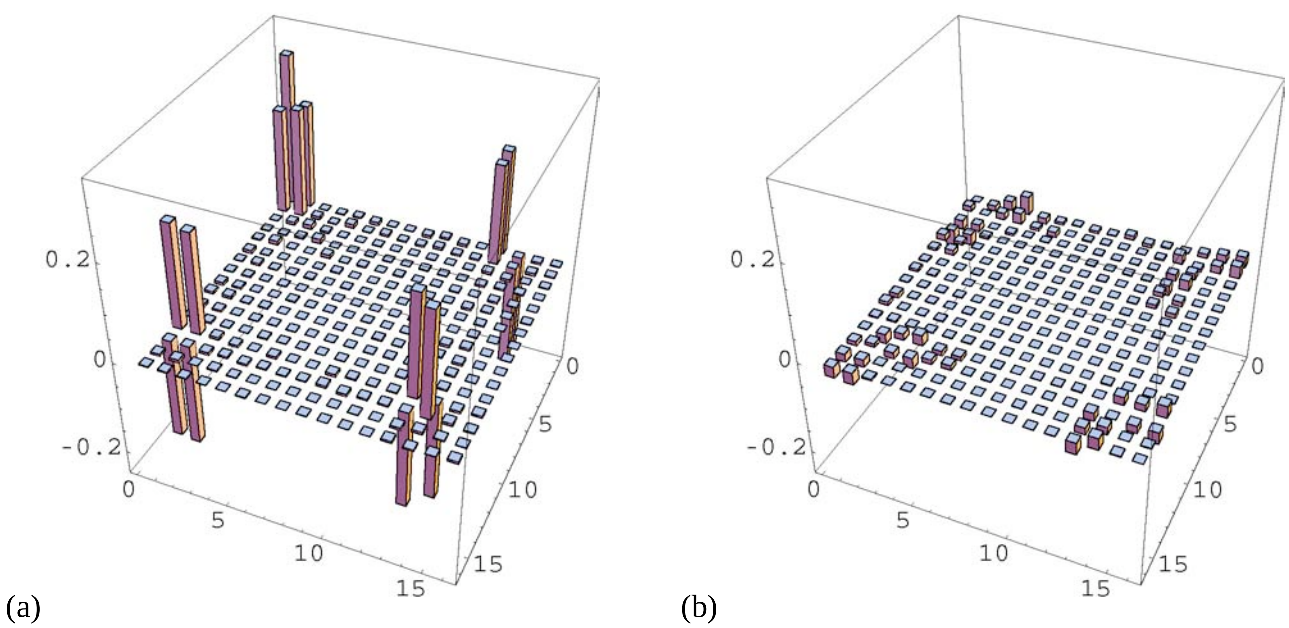

Fig 4. (a) Maximum-likelihood real part, and (b) maximum-likelihood imaginary part of the process matrix for our CNOT gate, corresponding to a decomposition of the process in the Pauli basis. The numbers on the x & y axes label the sixteen ordered pairwise combinations of the Pauli operators, $\{I, X, Y, Z\} \otimes \{I, X, Y, Z\}$.

Of course, one of the main uses of a physical process matrix is its use in predicting the operation of the gate for various input states. This enables all sorts of investigations of the gate properties, including the entangling power of the gate and its mixture. In Figure 5, we show scatter plots of the gate (state) fidelity and change in tangle vs. added mixture for a large number of pure input states uniformly distributed over the state space. It is important to note that predictions of this sort are only meaningful if the process matrix predicts physical output states. This work was published as J. L. O'Brien, G. J. Pryde, A. Gilchrist, D. F. V. James, N. K. Langford, T. C. Ralph, and A. G. White, Phys. Rev. Lett. **93**, 080502 (2004). An alternative method for obtaining a physical process matrix by first modelling the gate in a higher dimensional Hilbert space has been described in “Quantum Gate Characterization in an Extended Hilbert Space”, P.P.Rohde, G.J.Pryde, J.L.O’Brien and T.C.Ralph, submitted to Phys.Rev.Lett. quant-ph/0411144 (2004).

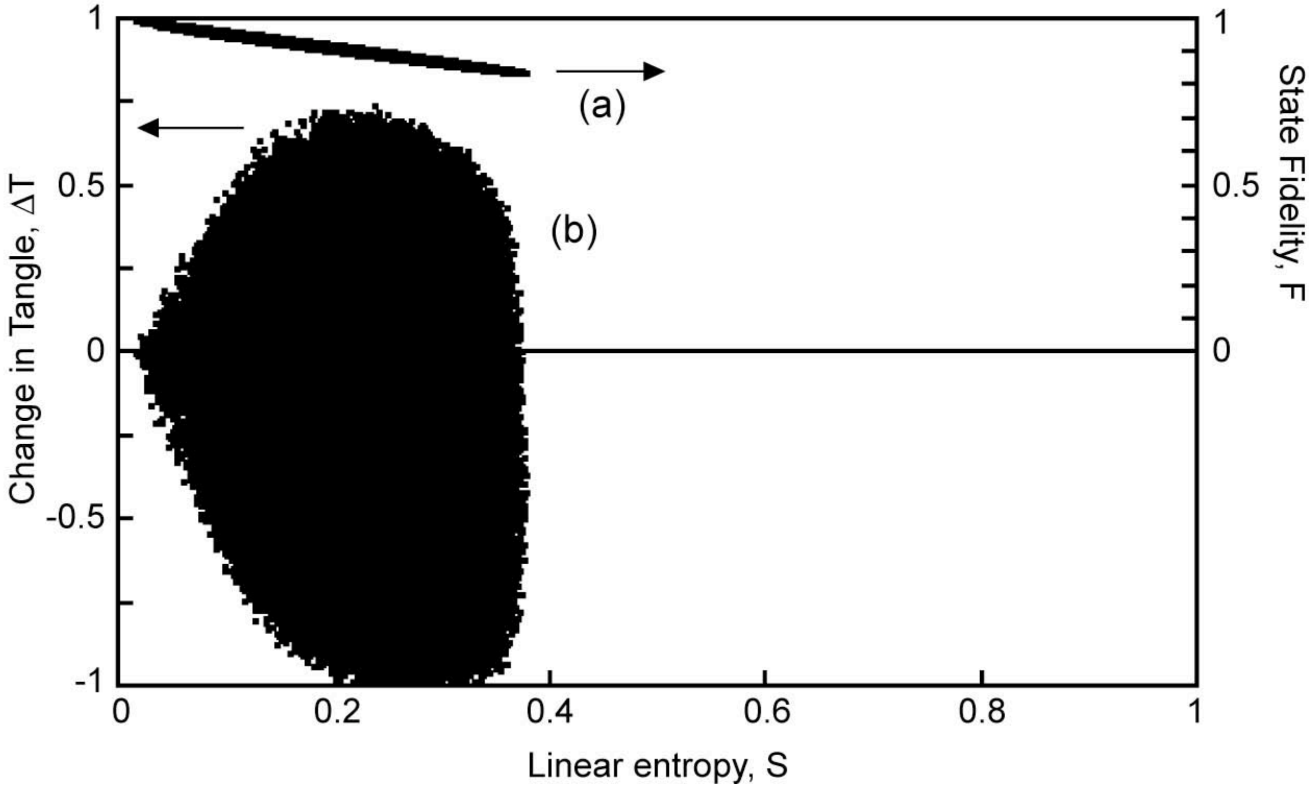

Fig 5. (a) State fidelity of our CNOT gate outputs (with ideal CNOT output states) calculated from the process matrix, plotted against the linear entropy added by the gate. A perfect experimental CNOT process would have F=1, S=0 for all states. (b) Change in tangle between input and output, and linear entropy added, for our CNOT gate outputs, calculated from the process matrix. An ideal CNOT would have points distributed between -1 and 1 on the y axis, and S=0. For both plots, the gate inputs were ~200,000 pure states uniformly distributed in the state space.

Z-Measurement Error Correction:

Quantum error correction works by encoding the quantum information over a number of physical qubits in such a way that measurements of the qubits can extract information about errors without destroying the fragile quantum information. If the frequency of errors is below some fault tolerant threshold [8] then errors will not propagate, making large scale quantum computation possible in principle. As such, the ability to do high fidelity error correction is a key requirement.

A simple error correction code is the one introduced by Knill, Laflamme and Milburn (KLM) [3] to protect against computational basis measurements (Z-measurements) of the qubits. A logical qubit can be encoded across 2 physical qubits as

$$\alpha\,|0\rangle_L + \beta\,|1\rangle_L = \alpha\,(|0\rangle\,|0\rangle + |1\rangle\,|1\rangle) + \beta\,(|0\rangle\,|1\rangle + |1\rangle\,|0\rangle). \qquad \text{Eq.(1)}$$

This is a parity encoding. The zero state is represented by all the even parity combinations of the 2 qubits whilst the one state is represented by all the odd parity combinations. Similarly a logical qubit can be encoded across n qubits by representing logical zero by all the even parity combinations of the n qubits and logical one by all the odd parity combinations. Notice that if a Z-measurement is made on either of the physical qubits of the state in Eq.1 and the result "0" is obtained, then the state collapses to an unencoded qubit, however the superposition is preserved. Similarly if the measurement result is "1" a bit-flipped version of the unencoded qubit is the result, but again the superposition is preserved so the qubit can be recovered. If the logical qubit is encoded across n physical qubits then a Z-measurement on any one of the qubits reduces the state to a logical qubit encoded across (n-1) physical qubits, but once again the superposition is preserved.

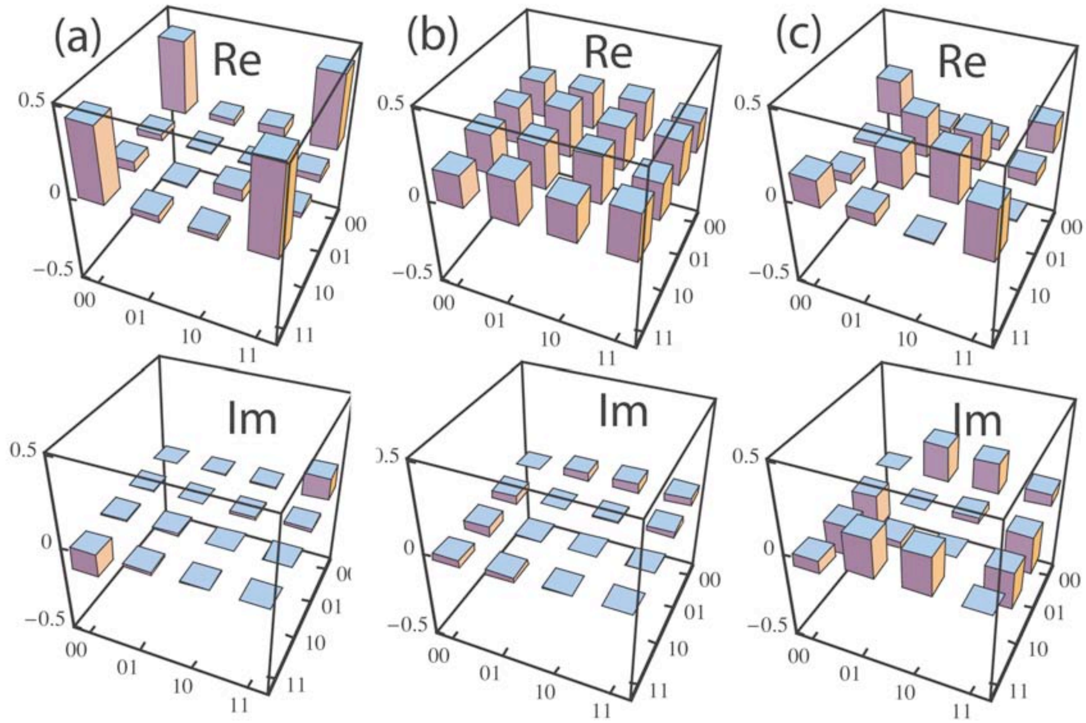

Fig.6: Density matrixes for the encoded states obtained when the initial states: (a) $|0\rangle$; (b) $|0\rangle + |1\rangle$ and; (c) $|0\rangle + i\,|1\rangle$ are inserted. The average fidelity with the expected states is 88%.

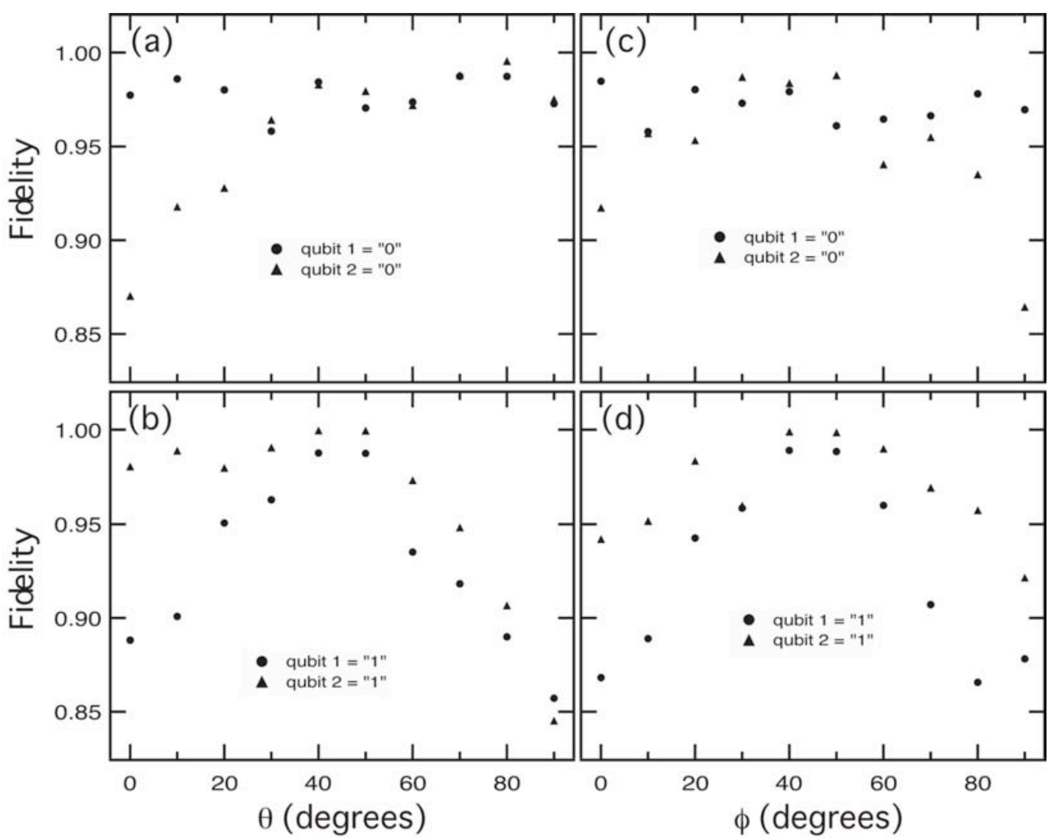

Fig.7: One qubit decoded state fidelities for the input states $\cos\theta\,|0\rangle + \sin\theta\,|1\rangle$ and $|0\rangle + \exp[i(90^{o} - 2\phi)]\,|1\rangle$.

This type of error correction is a key tool in the scale up strategy for LOQC circuits. KLM showed that the non-deterministic teleported CNOT gate they introduced [3] (or equivalently the Pittman et al CNOT gate [9]) failed by performing a Z-measurement on one of the qubits. Thus by using this encoding technique the qubits can be protected against gate failures and hence the effective success rate of gate operations can be boosted [10]. A similar principle underlies LOQC schemes based on cluster states [11,12] where again the cluster state structure is not destroyed by accidental Z-measurements. Parity encoding also forms the basis of encoding schemes against photon loss. Because of this key role it is of considerable importance to show that qubit states can be encoded and recovered after Z-measurements with high fidelity.

We have used our two photon CNOT gate to make such a demonstration. The encoded state is produced by using the qubit as the target input for the CNOT gate and an equal superposition state as the control. State tomography of the resulting encoded states for various input qubits are shown in Figure 6. The average fidelity between these output states and the ideal encoded states (as given by Eq.1) is 88%. We then decode the states by measuring either of the encoded qubits in the computational basis and then performing state tomography on the remaining qubit to observe how accurately we have recovered the original qubit. We do not optically correct for the bit flips detected by the error syndrome measurement. The results for a large range of initial qubits are shown in Figure 7. The average fidelity of the reconstructed qubit with the original qubit (or its bit flip for the case of a “1” measurement result) is 96%. This work has been submitted for publication as “High-Fidelity Z-Measurement Error Correction of Optical Qubits”, J.L.O'Brien, G.J.Pryde, A.G.White, T.C.Ralph, submitted to Phys.Rev.Lett. (2004).

Blueprints for Large Scale Processors

The original KLM scheme provided a blueprint for scale-up from the basic non-deterministic gates which have been the subject of our in principle demonstrations, to efficient multi-qubit quantum processing. However the overheads in terms of single photon sources and feed-forward are seemingly prohibitively large in the original scheme. We have described two alternatives to the original scheme, which have significantly reduced overheads.

We have considered a variation on the original KLM proposal that uses an incremental (as opposed to concatenation) approach to the encoding against teleportation errors. A key technique in this approach is to use re-encoding to achieve operations on the logical qubits, thus making large savings in over-heads. This approach has a number of parallels with the cluster state approach [10] and cross-fertilization between the two is proving very fruitful. This work has been published as A.J.F.Hayes, A.Gilchrist, C.R.Myers, T.C.Ralph, J. Opt. B: Quantum Semiclass. Opt. **6**, 533 (2004).

A quite different approach is to consider encoding qubits on multi-photon coherent states of light. A linear optics quantum computation scheme based on such an encoding was described by Ralph, Munro and Milburn [13]. The original scheme required prohibitively large superposition states (cat states) as a resource however we have shown that this problem can be avoided such that only “small” superposition states (~4 photons on average) are needed. The relaxation of the need for “large” coherent amplitudes is achieved using a number of new teleportation techniques. We also show that the error correction structure for coherent qubits has desirable properties. This work was published as T.C.Ralph, A.Gilchrist, G.J.Milburn, W.J.Munro and S.Glancy, Phys. Rev. A **68**, 042319 (2003).

<u>3. Papers.</u>

(a) Peer reviewed journals:
(i) “Linear Optical Controlled-not Gate in the Coincidence Basis”, T. C. Ralph, N. K. Langford, T. B. Bell and A. G. White, Physical Review A **65**, 062324 (2002).
(ii) “Entanglement creation using quantum interrogation, A. Gilchrist, A. G. White, and W. J. Munro, Physical Review A **66**, 012106 (2002).

(iii) “Nondeterministic gates for photonic single-rail quantum logic”, A. P. Lund and T. C. Ralph, Physical Review A **66**, 032307 (2002).
(iv) “Comparison of LOQC C-sign gates with ancilla inefficiency and an improvement to functionality under these conditions”, A.P.Lund, T.B.Bell and T.C.Ralph, Phys.Rev.A **68**, 022313 (2003).
(v) “Input states for quantum gates”, A.Gilchrist, W.J.Munro, and A.G.White, Phys. Rev. A **67**, 040304 (2003).
(vi) “Demonstration of an all-optical quantum controlled-not gate”, J.L.O’Brien, G.J.Pryde, A.G.White, T.C.Ralph and D.Branning, Nature **426**, 264 (2003).
(vii) “Photon-added Detection”, A.M.Branaczyk, T.J.Osborne, A.Gilchrist, T.C.Ralph, Phys. Rev. A **68**, 043821 (2003).
(viii) “Experimental requirements for Grover's algorithm in optical quantum computation”, J. L. Dodd, T. C. Ralph, and G. J. Milburn, Phys. Rev. A **68**, 042328 (2003).
(ix) “Quantum Computation with Coherent Optical States”, T.C.Ralph, A.Gilchrist, G.J.Milburn, W.J.Munro and S.Glancy, Phys. Rev. A **68**, 042319 (2003).
(x) “Creation of maximally entangled photon-number states using optical fiber multiports”, G. J. Pryde and A. G. White, Phys. Rev. A **68**, 052315 (2003).
(xi) “Measuring a photonic qubit without destroying it”, G.J.Pryde, J.L.O’Brien, A.G.White, S.D.Bartlett and T.C.Ralph, Phys. Rev. Lett. **92**, 190402 (2004).
(xii) “Scaling of Multiple Post-selected Quantum Gates in Optics”, T.C.Ralph, Phys.Rev.A **70**, 012312 (2004).
(xiii) “Quantum Process Tomography of a Controlled- NOT Gate”, J. L. O'Brien, G. J. Pryde, A. Gilchrist, D. F. V. James, N. K. Langford, T. C. Ralph, and A. G. White, Phys. Rev. Lett. **93**, 080502 (2004).
(xiv) “Utilizing Encoding in Scalable Linear Optics Quantum Computing”, A.J.F.Hayes, A.Gilchrist, C.R.Myers, T.C.Ralph, J. Opt. B: Quantum Semiclass. Opt. **6**, 533 (2004).

(b) Papers in non-peer reviewed journals or conference proceedings:
(i) T.C.Ralph, G.J.Milburn and W.J.Munro, "Quantum Computation with Optical Coherent States", in OSA *Trends in Optics Vol74, Quantum Electronics and Laser Science Conference*, OSA Technical Digest, (Optical Society of America, Washington DC 2002), pp264-265.
(ii) G.J.Milburn, "Quantum Computation using Linear Optics", in OSA *Trends in Optics Vol74, Quantum Electronics and Laser Science Conference*, OSA Technical Digest, (Optical Society of America, Washington DC 2002), pp222.
(iii) “Efficient Linear Optical Quantum Computation” A. G. White, T. B. Bell, N. K. Langford, G. J. Milburn J. L. O’Brien, G. J. Pryde, and T. C. Ralph, IQEC/LAT 2002 Technical Digest, p 107, 2002.
(iv) “Quantum computation based on linear optics” T.C.Ralph, W.J.Munro and G. J. Milburn, Proceedings of SPIE **4917**, 1 (2002).
(v) “Quantum Computing with Photons”, A.G.White, Bulletin of the American Physical Society, **13**, 1105 (2003).

(c) Papers presented at meetings:
“Quantum Computing with Light”, Invited talk T.C.Ralph, ESF Quantum Optics conference in San Feliu de Guixols, Spain, 6-11 October 2001.
"Quantum computation with single photons and coherent pulses", G.J.Milburn, 2nd European Comission Workshop QIPC, Italy 28-31 October.
“Quantum Information in Optics”, T.C.Ralph, Keynote address, ACOLS 2001, Brisbane, Australia, 3-6 December 2001.
“Efficient Linear Optics Quantum Computation", A.G.White, ACOLS 2001, Brisbane, Australia, 3-6 December 2001.
"Quantum Process Tomography", N.K.Langford, ACOLS 2001, Brisbane, Australia, 3-6 December 2001.
"The challenge of quantum technology", G.J.Milburn, Program on Quantum Information, Institute for theoretical physics, UC Santa Barbara Nov 21-Dec 14 2001.
"Something for now, something for later: Quantum information in optics", T.C.Ralph, invited talk, Quantum Information Processing with Continuous Variables Workshop, Brussels Belgium, April 2002.
“Can we build an optical quantum computer?”, G. J. Milburn, Invited Talk, QCMC’02, MIT Boston 2002

“Single Rail Quantum Logic in Optics”, T. C. Ralph and A. P. Lund, Poster, QCMC’02, MIT Boston 2002
“Efficient Linear Optical Quantum Computation”, A. G. White, G. J. Pryde, J. L. O’Brien, T. B. Bell, N. K. Langford, G. J. Milburn, T. C. Ralph, and Q. Wang, Talk, QCMC’02, MIT Boston 2002.
“Using Quantum Process Tomography in Optics”, N. K. Langford, A.G.White and T.C.Ralph, Talk, AIP Congress, Sydney 2002.
“Single Rail Quantum Logic in Optics”, A.P.Lund and T.C.Ralph, Talk, AIP Congress, Sydney 2002.
“Experimental implementation of efficient linear optics quantum computation”, J.L.Obrien, T. B. Bell, N. K. Langford, G. J. Milburn J. L. O’Brien, G. J. Pryde, T. C. Ralph and A.G.White, , Talk, AIP Congress, Sydney 2002.
“Linear optics quantum logic gates in the real world”, T.B.Bell, N.K.Langford, A.G.White and T.C.Ralph, Talk, AIP Congress, Sydney 2002.
“Linear optical quantum computation”, A. G. White, T. B. Bell, N. K. Langford, G. J. Milburn J. L. O’Brien, G. J. Pryde, T. C. Ralph, and Q. Wang, Invited Talk, Feynman Festival, UMBC, Baltimore, 2002.
“Scalable quantum computation with linear optics” T.C.Ralph, Invited Talk, Laser Science XVIII, Orlando, USA (2002).
“Optical Quantum Computing”, A.G.White, invited talk, COMMAD, Sydney, Australia (2002).
“ELOQC”, A.G.White, invited talk, IQEC, Moscow, Russia (2002).
“Physical Implementations of Quantum Computing”, A.G.White, invited talk, QICSS (2002).
“Optical Quantum Computing”, G. J. Milburn and T. C. Ralph, invited talk at US/Australia Workshop on Solid State and Optical Approaches to Quantum Information Science, Newport, Australia, 6th January (2003).
“Scalable Linear Optics Quantum Computing”, J. L. O’Brien and G. J. Pryde, invited talk at US / Australia Workshop on Solid State and Optical Approaches to Quantum Information Science, Newport, Australia, 7th January (2003).
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5. Inventions.

NA

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7. Appendixes

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